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To Whom It May Concern:

Please find herein enclosed the final report for the NASA Long-Term Space Astrophysics Grant "BL Lacertae Objects", J.T. Stocke (PI): NAGW-2675. This final report includes a description of the work accomplished and the personnel supported in pursuance of this work. I have also enclosed copies of all the publications that this grant has supported or partially supported over the course of this grant period.

Sincerely Yours,

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## A SUMMARY OF BL LAC RESULTS FUNDED BY NASA/LTSA

In the last six years research on BL Lacertae Objects at Colorado included the thesis research of Dr. Eric Perlman (now a postdoc at STScI), Dr. Ron Wurtz (now a postdoc at Lawrence Livermore Labs) and Mr. Travis Rector (thesis in progress). This grant also partially supported Dr. Erica Ellingson in a postdoctoral research position. Dr. Ellingson is now a faculty member in our department. Thus, this grant has contributed to one of the original goals of the NAS/LTSA program, the goal of junior faculty development. Below I briefly summarize the following major results on BL Lacertae Objects that we have obtained (the publications referred to by number in parentheses below are listed at the end of this section). An invited talk by this PI on BL Lac Objects at IAU 175 "Extragalactic Radio Sources" at Bologna Italy in October 1995 summarized some of these results. A second invited talk in Oct 1998 at Green Bank, WVA presented other BL Lac results at the conference entitled: "Highly Redshifted Radio Lines".

### 1. X-ray Selected BL Lac Objects:

\* We have used the EMSS sample to measure the X-ray luminosity function and cosmological evolution of BL Lacs and found surprisingly that  $\langle V/V_{max} \rangle = 0.33 \pm 0.06$  (2,12), a dramatically different value from that found ( $0.60 \pm 0.05$ ; Stickel et al. 1991 & 20) for the only complete RBL sample (1 Jy). While the 1 Jy result may be affected by the lack of firm redshifts for  $\sim 20\%$  of the sample, we have used new techniques and high signal-to-noise ratio (SNR) spectroscopy to measure firm redshifts for 25 of 27 EMSS XBLs (2,12). Extending this sample to lower fluxes and luminosities is in progress to better determine the luminosity function and cosmological evolution of XBLs. The  $\langle V/V_{max} \rangle$  discrepancy remains as the primary objection to the unification of XBLs and RBLs into a single class.

\* ROSAT HRI Imaging of several EMSS sources originally identified with clusters of galaxies has found that a few are actually BL Lacs (19), substantiating the contention of Browne & Marcha (1993) that low luminosity BL Lacs should exist. Three of these are in the Morris et al. (1991) complete sample but do not alter substantially the  $\langle V/V_{max} \rangle$  value mentioned above.

\* VLA mapping (5) has been used to show that the extended radio powers and morphologies of XBLs are consistent with XBLs being beamed FR-1s and core dominance values for XBLs are intermediate between FR-1s and RBLs, suggesting (for a typical  $\gamma \sim 5$ ) mean viewing angles for RBLs and XBLs of  $8^\circ$  and  $24^\circ$  respectively, consistent with their space densities and other estimation methods (Urry & Padovani 1995). These data strongly support the beamed FR-1 hypotheses.

\* The X-ray spectra of XBLs and RBLs have nearly indistinguishable spectral slopes in the ROSAT PSPC band (12,13), approximately  $1/2$  unit steeper in power-law spectral index than quasars. These observations support the Guilbert, Fabian & McCray (1983) hypothesis that BL Lacs are lineless because the softness of their X-ray spectral slopes is insufficient to create quasi-stable broadline clouds. If this hypothesis is correct the only region which "sees" the hard inverse-Compton emission found in RBLs is within a few degrees of the radio jet axis (12).

\* A new large sample of XBLs has been discovered and conclusively identified using the Einstein "Slew Survey" (6,14). The Slew now contains 62 BL Lacs and the 43 member complete sample of northern Slew BL Lacs is the largest complete sample of BL Lacs known (see Figure 1 in Section IIIA below). The discovery of this new BL Lac sample used an extremely efficient (90% of identified candidates are confirmed as BL Lacs) X-ray/radio method proposed by this PI (14).

### 2. Radio Selected BL Lac Objects:

\* Very high dynamic range radio maps of those few RBLs unresolved by previous observations (9) found that most were consistent with the beamed FR-1 hypothesis. Further VLA mapping has now resolved and mapped those 1 Jy BL Lacs not well-mapped in the past (20).

- BL Lac In or Behind a Spiral Galaxy?", *ApJL* 400, L17.
5. Perlman, E. and Stocke, J. 1993, "The Radio Structure of X-ray Selected BL Lacertae Objects", *ApJ* 406, 430.
  6. Schachter, J., Stocke, J., Perlman, E., Elvis, M., Remillard, R., Granados, A., Luu, J., Huchra, J., Humphreys, R., Urry, M., and Wallin, J. 1993, "Ten New BL Lacertae Objects Discovered by an Efficient X-ray/Radio/Optical Technique", *ApJ* 412, 541.
  7. Wurtz, R., Ellingson, E., Stocke, J., and Yee, H. 1993, "Clustering Environments of BL Lac Objects", *AJ* 106, 869.
  8. Perlman, E., Stocke, J., Shaffer, D., Carilli, C., and Ma, C. 1994, "High Dynamic Range Radio Observations of PKS 1413+135: A BL Lacertae Object with a Parsec-Scale Counterjet", *ApJL* 424, L69.
  9. Perlman, E. and Stocke, J. 1994, "New Very Large Array Maps of Highly Core-Dominated BL Lacs: Testing Unified Schemes", *AJ* 108, 56.
  10. Stocke, J.T., Wurtz, R.E., and Perlman, E.S. 1995, "MS 0205.7+3509: A Microlensed BL Lac Candidate", *ApJ* 454, 55.
  11. Stocke, J.T., Shull, J.M., Penton, S., Donahue, M., and Carilli, C. 1995, "The Local Ly $\alpha$  Forest: Association of Clouds with Superclusters and Voids", *ApJ* 451, 24.
  12. Perlman, E.S., Stocke, J.T., Wang, Q.D., and Morris, S.L. 1996, "Soft X-ray Observations of a Complete Sample of X-ray Selected BL Lacertae Objects", *ApJ* 456, 451.
  13. Urry, C.M., Sambruna, R.M., Worrall, D.M., Kollgaard, R.I., Feigelson, E.D., Perlman, E.S., and Stocke, J.T. 1996, "Soft X-ray Properties of a Complete Sample of Radio-Selected BL Lacertae Objects", *ApJ* 463, 424.
  14. Perlman, E.S., Stocke, J.T., Schachter, J.F., Elvis, M., Ellingson, E., Urry, C.M., Potter, M., Impey, C.D., and Kolchinsky, P. 1996, "The Einstein Slew Survey Sample of BL Lacs", *ApJS* 104, 251.
  15. Wurtz, R., Stocke, J., and Yee, H.K.C. 1996, "The CFHT Imaging Survey of BL Lacertae Objects I: Properties of the Host Galaxies", *ApJS* 103, 109.
  16. Perlman, E.S., Carilli, C., Stocke, J.T., and Conway, J. 1996, "Multi-Frequency VLBA Mapping of PKS 1413+135: A Very Young Radio Galaxy", *AJ* 111, 1839.
  17. Wurtz, R., Stocke, J., Ellingson, E., and Yee, H.K.C. 1997, "The CFHT Imaging Survey of BL Lacertae Objects II: Clustering Environments", *ApJ* 480, 547.
  18. Stocke, J.T. & Rector, T.A. 1997, "An Excess of Mg II Absorbers in BL Lacertae Objects" *ApJL*, 489, L17.
  19. Rector, T.A., Stocke, J.T. & Perlman, E.S. 1998, "A ROSAT Search for Low Luminosity BL Lac Objects", *AJ*, submitted.
  20. Rector, T.A. & Stocke, J.T. 1998, "The Radio and Optical Properties of 1 Jy BL Lacertae Objects", in preparation.

#### IV. REFERENCES

- Browne, I.W.A. & Marcha, M. 1993 *MNRAS*, 261, 795.
- Guilbert, P.W., Fabian, A.C. & McCray, R. 1983 *ApJ* 266, 466
- Morris, S.L., Stocke, J.T., Gioia, I.M., Schild, R.E., Wolter, A., Maccacaro, T. & Della Ceca, R. 1991 *ApJ* 380, 49.
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- Stickel, M., Padovani, P., Urry, C.M., & Fried, J.W. 1991 *ApJ* 374, 431.
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- Wiklind, T. & Combes, F. 1995 *A&A* 299, 382.

\* However, one source, PKS 1413+135, has no extended radio structure  $> 200$  pc, its VLBI structure (8,16) is that of a compact symmetric object (CSO) and its host galaxy is a spiral (15). Soft X-ray and H I 21 cm absorptions found by us (3,4) led to the discovery of the first high- $z$  molecular absorptions by Wiklind & Combes (1995). As one of the nearest CSOs, PKS 1413+135 could be our first clear example of how radio-loud AGNs are created through mergers of gas-rich disk systems or, alternately, it could be a gravitationally-lensed BL Lac (16). The similarity between PKS 1413+135 and other highly-reddened and possibly lensed systems (e.g. 0218+357) has led to other H I and molecular absorption detections and new interest in highly reddened quasars.

\* Hubble Space Telescope (HST) Goddard High-Resolution spectrometer (GHRS) far-UV spectra of very bright BL Lacs have led to the discovery of Ly $\alpha$  absorption lines in nearby galaxy voids (11) suggesting that at least some of these clouds are “pristine” intergalactic material and that the voids are not completely empty of matter. The first solid detection of broad Ly $\alpha$  emission has also been made with these spectra (in Markarian 501; 11).

### 3. BL Lacs in general:

\* Deep optical imaging of 50 XBLs and RBLs have been obtained at the Canada-France-Hawaii 3.6m Telescope (CFHT; 15,17). All but 4 BL Lac images were resolved and host galaxy luminosities obtained ( $<M_r> = -23.2$  for  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). Unambiguous host galaxy morphologies were determined for 80% of these and all but 3 (including PKS 1413+135) were found to be ellipticals. One of the three spiral has an offset core (MS 0205+531) and is likely a gravitationally-lensed BL Lac (10).

\* Surprisingly, the host galaxy luminosity distribution (15) and clustering environments (17) of BL Lacs are more consistent with FR 2s than with FR-1s. But since it is well-known that the extended radio luminosities of BL Lacs are very consistent with FR-1s, we hypothesize that these new results derive from the likelihood that rich cluster radio galaxies, specifically the brightest cluster galaxies, cannot be seen as BL Lacs (15,17). While the physical reason for this result remains obscure, this does explain the failure to find low luminosity BL Lacs among a large sample of rich cluster FR-1s (Owen, Ledlow & Keel 1996).

\* While the typical BL Lac cluster environment at low redshift is in richness  $\leq 0$  clusters, there is evolution in BL Lac environments similar to that seen for quasars (15,17). So we have found a few BL Lacs in rich clusters at  $z \geq 1/2$  (7), which will be useful for galaxy evolution studies.

\* The most surprising result on BL Lacs has come recently from our high signal-to-noise-ratio optical spectroscopy of 1 Jy BL Lacs (20) in which we have found a large excess (factor 4-5) in the number of Mg II absorption line systems per unit redshift compared to quasars from the Steidel & Sargent (1992) survey (18). We interpret this results as a strong indicator that many high- $z$  RBLs are gravitationally lensed by foreground stars, which is the only way to easily reconcile why there should be a correlation between the presence of a foreground absorber and the optical properties of the background sources (i.e., nearly featureless optical spectrum). Due to this surprising result, a portion of this proposed reasearch is devoted to obtaining higher resolution optical spectroscopy (particularly in the near-UV) to discover new Mg II absorption systems in BL Lacs.

BL Lac Publications by Stocke (PI) and collaborators supported by this LTSA Grant (at least partially). Copies of all published articles are included with this report.

1. Stocke, J.T., Morris, S.L., Fleming, T.A., Maccacaro, T., and Henry, J.P. 1991, “The Einstein Observatory Extended Medium Sensitivity Survey II: The Optical Identifications,” *ApJS* 76, 813.
2. Morris, S., Stocke, J.T., Gioia, I., Schild, R., Wolter, A., Maccacaro, T., and Della Ceca, R. 1991, “The Luminosity Function and Cosmological Evolution of X-ray Selected BL Lac Objects”, *ApJ* 380, 49.
3. Carilli, C., Perlman, E., and Stocke, J. 1992, “Discovery of Neutral Hydrogen 21 cm Absorption at Redshift 0.25 Towards PKS 1413+135”, *ApJL* 400, L13.
4. Stocke, J., Wurtz, R., Wang, Q., Januzzi, B., Elston, R., and Deiker, S. 1992, “PKS 1413+135: A